Executive Summary

The *Printed Wiring Board Cleaner Technologies Substitutes Assessment: Making Holes Conductive* is a technical document that presents comparative risk, competitiveness, and resource requirements information on seven technologies for performing the "making holes conductive" (MHC) function during printed wiring board (PWB) manufacturing. MHC technologies are used by PWB manufacturers to deposit a seed layer or coating of conductive material into the drilled through-holes of rigid, multi-layer PWBs prior to electroplating. Volume I describes the MHC technologies, methods used to assess the technologies, and cleaner technologies substitutes assessment (CTSA) results. Volume II contains appendices, including detailed chemical properties and methodology information, as well as comprehensive results of the exposure assessment and risk characterization.

Information presented in the CTSA was developed by the U.S. Environmental Protection Agency (EPA) Design for the Environment (DfE) Printed Wiring Board (PWB) Project and the University of Tennessee (UT) Center for Clean Products and Clean Technologies. The technologies evaluated are electroless copper, carbon, conductive polymer, graphite, non-formaldehyde electroless copper, organic-palladium, and tin-palladium. Chemical and process information is also presented for a conductive ink technology, but this technology is not evaluated fully.[1]

The DfE PWB Project is a voluntary, cooperative partnership among EPA, industry, public-interest groups, and other stakeholders to promote implementation of environmentally beneficial and economically feasible manufacturing technologies by PWB manufacturers. Project partners participated in the planning and execution of this CTSA by helping define the scope and direction of the CTSA, developing project workplans, reviewing technical information contained in this CTSA, and by donating time, materials, and their manufacturing facilities for project research. Much of the process-specific information presented here was provided by chemical suppliers to the PWB industry, PWB manufacturers who completed project information requests, and PWB manufacturers who volunteered their facilities for a performance demonstration of the baseline and alternative technologies.

The CTSA is intended to provide PWB manufacturers with information that can assist them in making decisions that incorporate environmental concerns along with performance and cost information when choosing an MHC technology. While the DfE PWB Project is especially designed to assist small-and medium-sized PWB manufacturers who may have limited time or resources to compare MHC technologies, the primary audience for the CTSA is environmental health and safety personnel, chemical and equipment manufacturers and suppliers in the PWB manufacturing industry, community groups concerned about community health risks, and other technically informed decision-makers.

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[1] Only limited analyses were performed on the conductive ink technology for two reasons: 1) the process is not applicable to multi-layer boards, which were the focus of the CTSA; and 2) sufficient data were not available to characterize the risk, cost, and energy and natural resources consumption of all of the relevant process steps (e.g., preparation of the screen for printing, the screen printing process itself, and screen reclamation).

I. DESIGN FOR THE ENVIRONMENT PRINTED WIRING BOARD PROJECT

The DfE PWB Project is a joint effort of the EPA DfE Program and the UT Center for Clean Products and Clean Technologies in voluntary and cooperative partnerships with the PWB industry national trade association, the Institute for Interconnecting and Packaging Electronic Circuits (IPC); individual PWB manufacturers and suppliers; the industry research consortium, Microelectronics and Computer Technology Corporation (MCC); and public-interest organizations, including Silicon Valley Toxics Coalition and Communities for a Better Environment.

In part, the project is an outgrowth of industry studies to identify key cleaner technology needs in electronic systems manufacturing. These studies include *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics Industry* (MCC, 1993) and *Electronics Industry Environmental Roadmap* (MCC, 1994). The latter study identified wet chemistry processes, such as the traditional electroless copper process for performing the MHC function, as potentially significant sources of hazardous waste, which require substantial amounts of water and energy, and use chemicals that may pose environmental and health risks. The potential for improvement in these areas led EPA's DfE Program to forge the working partnerships that resulted in the DfE PWB Project.

EPA's Design for the Environment Program

The EPA DfE Program was formed by the Office of Pollution Prevention and Toxics to use EPA's expertise and leadership to facilitate information exchange and research on risk reduction and pollution prevention opportunities. DfE works on a voluntary basis with mostly small- and medium-sized businesses to evaluate the risks, performance, costs, and resource requirements of alternative chemicals, processes, and technologies.

Additional goals of the program include:

- Changing general business practices to incorporate environmental concerns.
- Helping individual businesses undertake environmental design efforts through the application of specific tools and methods.

DfE Partners include:

- Industry
- Professional institutions
- Academia
- Public-interest groups
- Other government agencies

Since its inception in 1994, the PWB Project has fostered open and active participation in addressing environmental challenges faced by the PWB industry. The Project has also identified, evaluated, and disseminated information on viable pollution prevention opportunities in the industry. Over the long-term, the Project seeks to encourage companies to consider implementing cleaner technologies that will improve the environmental performance and competitiveness of the PWB industry. Toward this goal, the CTSA presents the first complete set of information developed by the Project on the risk, competitiveness (i.e., cost, performance, etc.), and resource requirements of cleaner technologies.

II. OVERVIEW OF MHC TECHNOLOGIES

Until the late 1980s, virtually all PWB manufacturers employed an electroless copper plating process to accomplish the MHC function. This process is used to plate a thin layer of copper onto the hole walls to create the conductive surface required for electrolytic copper plating. Although the traditional electroless copper process is a mature technology that produces reliable interconnects, the typical process line is long (17 or more tanks, depending on rinse configurations) and may have eight or more process baths. It is also a source of formaldehyde emissions and a major source of wastewater containing chelated, complexed copper. In recent years, wastewater treatment requirements and new formaldehyde regulations have provided an impetus for an intensified search for less polluting alternatives.

Process Description

MHC processes typically consist of a series of sequential chemical processing tanks separated by water rinse stages. The process can either be operated in a vertical, non-conveyorized immersion-type mode, or in a horizontal, conveyorized mode. In either mode, selected baths may be operated at elevated temperature to facilitate required chemical reactions, or agitated to improve contact between the panels and the bath chemistry. Agitation methods employed by PWB manufacturers include panel agitation, air sparging, and fluid circulation pumps.

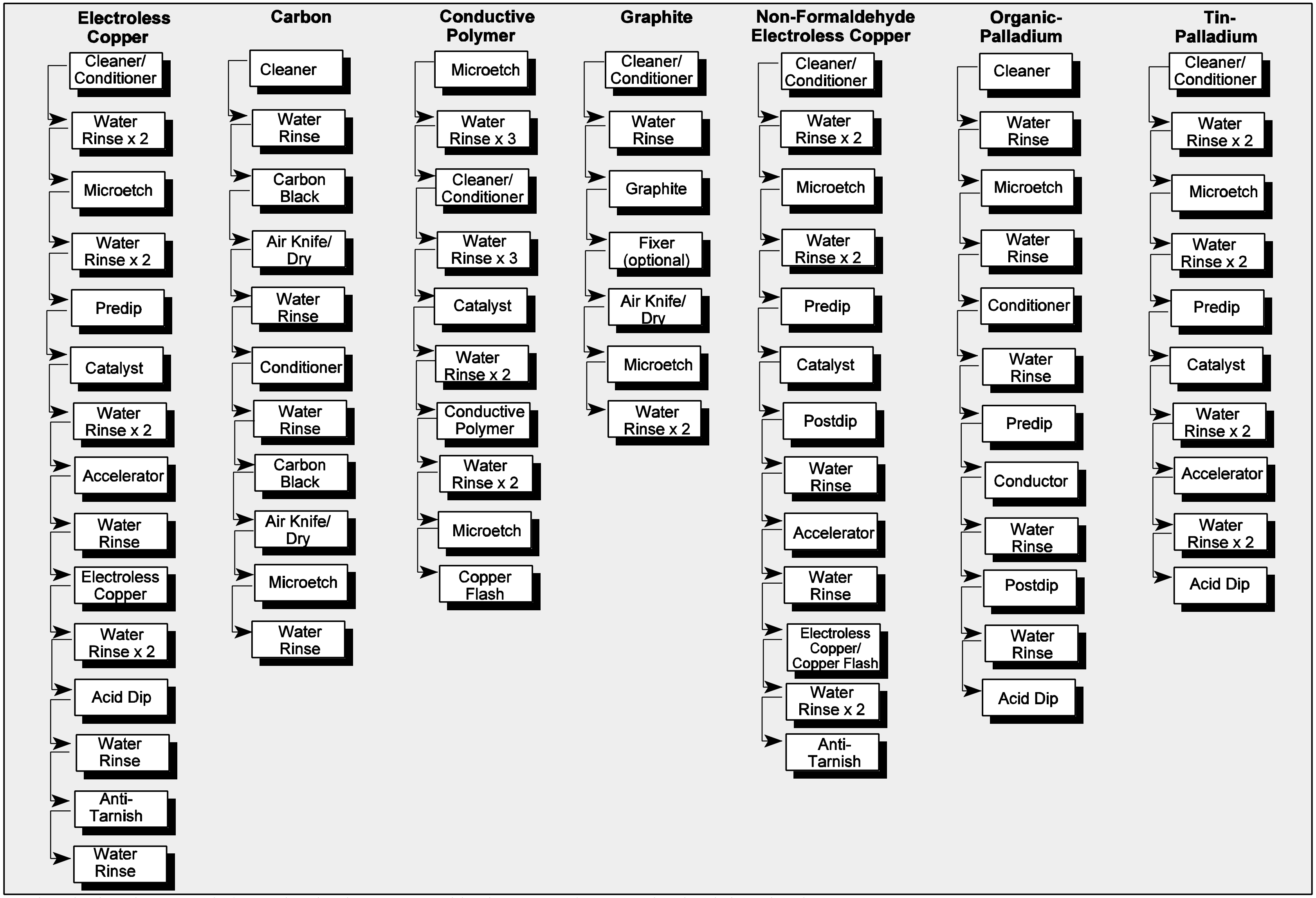
Most process baths are followed by a water rinse tank to remove drag-out (i.e., the clinging film of process solution covering the rack and boards when they are removed from a tank). Rinsing is necessary to clean the surface of the rack and boards and avoid contaminating subsequent process baths. Many PWB manufacturers employ a variety of rinse water reduction methods to reduce rinse water usage and consequent wastewater generation rates. The nature and quantity of wastewater generated from MHC process lines are discussed in Section 3.1, Source Release Assessment, while rinse water reduction techniques are discussed in Section 6.1, Pollution Prevention.

In the non-conveyorized mode, drilled multi-layered panels are loaded onto a rack, desmeared, and then run through the MHC process line. Racks may be manually moved from tank to tank, or moved by a manually controlled hoist or other means. Process tanks are usually open to the atmosphere. To reduce volatilization of chemicals from the bath or worker exposure to volatilized chemicals, process baths may be equipped with a local ventilation system, such as a push-pull system, bath covers for periods of inoperation, or floating plastic balls. Conveyorized systems are typically fully enclosed, with air emissions vented to a control technology or to the atmosphere outside the plant.

Generic Process Steps and Bath Sequences of MHC Technologies

Figure ES.1 presents the generic process steps and typical bath sequences evaluated in the CTSA. The process baths depicted in the figure are an integration of the various products submitted for evaluation by chemical suppliers within a technology category. For example, six different electroless copper processes were submitted by chemical suppliers for evaluation in the CTSA, and these and other suppliers offer additional electroless copper processes that may have slightly different bath chemistries or bath sequences. In addition, the bath sequences (bath order and rinse tank configuration) were aggregated from data collected from various PWB facilities using the different MHC technologies. Thus, Figure ES.1 lists the types and sequences of baths in generic process lines, but the types and sequence of baths in actual lines may vary.

Figure ES.1 Generic Process Steps and Typical Bath Sequences of MHC Technologies[a]



[a] Chemical and process information is also presented in the CTSA for a conductive ink technology.

Table ES.1 presents the processes evaluated in the CTSA. These are distinguished both by process technology and equipment configuration (e.g., non-conveyorized or conveyorized). The non-conveyorized electroless copper process is the industry standard for performing the MHC function and is the baseline process against which alternative technologies and equipment configurations are compared.

Table ES.1 MHC Processes Evaluated in the CTSA[a]

MHC Technology	Equipment Configuration	
	Non-Conveyorized	Conveyorized
Electroless Copper (BASELINE)	✓	✓
Carbon		✓
Conductive Polymer		✓
Graphite		✓
Non-Formaldehyde Electroless Copper	✓	
Organic-Palladium	✓	✓
Tin-Palladium	✓	✓

[a] The human health and aquatic toxicity hazards and chemical safety hazards of a *conductive ink technology* were also evaluated, but risk was not characterized.

III. CLEANER TECHNOLOGIES SUBSTITUTES ASSESSMENT METHODOLOGY

The CTSA methodology is a means of systematically evaluating and comparing human health and environmental risk, competitiveness (i.e., performance, cost, etc.), and resource requirements of traditional and alternative chemicals, manufacturing methods, and technologies that can be used to perform the same function. The publication, *Cleaner Technologies Substitutes Assessment: A Methodology & Resource Guide* (Kincaid et al., 1996), presents the basic CTSA methodology in detail. Chapters 2 through 6 in Volume I of the PWB MHC CTSA and the appendices in Volume II describe the particular methods used in this assessment.

Key to the successful completion of any CTSA is the active participation of manufacturers and their suppliers. This assessment was open to any MHC chemical supplier who wanted to submit a technology, provided the technology met the following criteria:

- It is an existing or emerging technology.
- There are equipment and facilities available to demonstrate its performance.

In addition, suppliers agreed to provide information about their technologies, including chemical product formulation data, process schematics, process characteristics and constraints (e.g., cycle time, limitations for the acid copper plating process, substrate and drilling compatibilities, aspect ratio capacity, range of hole sizes), bath replacement criteria, and cost information.

Issues Evaluated

The CTSA evaluated a number of issues related to the risk, competitiveness, and resource requirements (conservation) of MHC technologies. These include the following:

- Risk: occupational health risks, public health risks, ecological hazards, and process safety concerns.
- Competitiveness: technology performance, cost, regulatory status, and international market status.
- Conservation: energy and natural resource use.

Occupational and public health risk information is for chronic exposure to long-term, day-to-day releases from a PWB facility rather than short-term, acute exposures to high levels of hazardous chemicals as could occur with a fire, spill, or periodic release. Risk information is based on exposures estimated for a model facility, rather than exposures estimated for a specific facility. Ecological hazards, but not risks, are evaluated for aquatic organisms that could be exposed to MHC chemicals in wastewater discharges. Process safety concerns are summarized from material safety data sheets (MSDSs) for the technologies and process operating conditions.

Technology performance is based on a snapshot of the performance of the MHC technologies at volunteer test sites in the U.S. and abroad. Panels were electrically prescreened, followed by electrical stress testing and mechanical testing, in order to distinguish variability in the performance of the MHC interconnect. Comparative costs of the MHC technologies were estimated with a hybrid cost model that combines traditional costs with simulation modeling and activity-based costs. Costs are presented in terms of dollars per surface square feet (ssf) of PWB produced.

Federal environmental regulatory information is presented for the chemicals in the MHC technologies. This information is intended to provide an indication of the regulatory requirements potentially associated with a technology, but not to serve as regulatory guidance. Information on the international market status of technologies is presented as an indicator of the effects of a technology choice on global competitiveness.

Quantitative resource consumption data are presented for the comparative rates of energy and water use of the MHC technologies. The large amounts of water consumed and wastewater generated by the traditional electroless copper process have been of particular concern to PWB manufacturers, as well as to the communities in which they are located.

Data Collection

Determining the risks of the baseline and alternative MHC technologies required information on the MHC chemical products. Chemical information provided by chemical suppliers included the following publicly-available sources of information: MSDSs for the chemical products in their MHC technology lines; Product Data Sheets, which are technical specifications prepared by suppliers for PWB manufacturers that describe how to mix and maintain the chemicals baths; and, in some cases, copies of patents. Suppliers were also asked to provide the identities and concentrations of proprietary chemical ingredients to the project.

Electrochemicals, LeaRonal, and Solution Technology Systems provided information on proprietary chemical ingredients to the project. Atotech provided information on one proprietary chemical ingredient in one product line. W.R. Grace was preparing to provide information on proprietary chemical ingredients in the conductive ink technology when it was determined that this information was no longer necessary because risk from the conductive ink technology could not be characterized. The other suppliers participating in the project (Enthone-OMI, MacDermid, and Shipley) declined to provide any proprietary information on their MHC technologies. The absence of information on proprietary chemical ingredients is a significant source of uncertainty in the risk characterization. Risk information for proprietary ingredients, as available, is included in this CTSA, but chemical identities, concentration, and chemical properties are not listed.

Data Collection Forms

Appendix A in Volume II of the CTSA presents data collection forms used by the project, including the following:

- The IPC Workplace Practices Questionnaire, which requested detailed information on facility size, process characteristics, chemical consumption, worker activities related to chemical exposure, water consumption, and wastewater discharges.
- The Facility Background Information Sheet (developed from the IPC Workplace Practices Questionnaire), which was sent to PWB facilities participating in the Performance Demonstration prior to their MHC technology test date and requested detailed information on facility and process characteristics, chemical consumption, worker activities related to chemical exposure, water consumption, and wastewater discharges.
- The Observer Data Sheet, which was used by an on-site observer to collect data during the Performance Demonstration. In addition to ensuring that the performance test was performed according to the agreed upon test protocol, the on-site observer collected measured data, such as bath temperature and process line dimensions, and checked survey data for accuracy.
- The Supplier Data Sheet, which included information on chemical cost, equipment cost, water consumption rates, product constraints, and the locations of test sites for the Performance Demonstration.

Chemical Information

Appendix B presents chemical properties and selected environmental fate properties for the non-proprietary chemicals in MHC chemical products. Proprieties of proprietary chemical ingredients are not included to protect proprietary chemical identities. Properties that were measured or estimated (using a variety of standard EPA methods) included melting point, solubility, vapor pressure, octanol-water partition coefficient, boiling point, and flash point. These properties can be used to determine the environmental fate of the MHC chemicals when they are released to the environment.

Health Hazard Assessments

Inherent in determining the risk associated with the MHC chemicals is a determination of the hazard or toxicity of the chemicals. Human health hazard information for non-proprietary chemicals is presented in Section 3.3. Detailed toxicity data for proprietary chemicals are not included to protect proprietary chemical identities. Many of the chemicals in the MHC chemical products have been studied to determine their health effects, and data from those studies are available in published scientific literature. In order to collect available testing data for the MHC chemicals, literature searches were conducted of standard chemical references and on-line databases, including EPA's Integrated Risk Information System (IRIS), the National Library of Medicine's Hazardous Substances Data Bank (HSDB), TOXLINE, TOXLIT, GENETOX, and the Registry of Toxic Effects of Chemical Substances (RTECS).

For many of the chemicals, EPA has identified chemical exposure levels that are known to be hazardous if exceeded or met (e.g., no- or lowest-observed-adverse-effect level [NOAEL or LOAEL]), or levels that are protective of human health (reference concentration [RfC] or reference dose [RfD]). These values were taken from on-line databases and published literature. For many of the chemicals lacking toxicity data, EPA's Structure-Activity Team (SAT) estimated human health concerns based on analogous chemicals. Hazard information is combined with estimated exposure levels to develop an estimate of the risk associated with each chemical.

Ecological Hazard Assessments

Similar information was gathered on the ecological effects that may be expected if MHC chemicals are released to water. Acute and chronic toxicity values were taken from on-line database searches (TOXNET and ACQUIRE) or published literature, or were estimated using structure-activity relationships if measured data were not available. Based on the toxicity values, MHC chemicals were assigned concern concentrations (CCs). A CC is the concentration of a chemical in the aquatic environment which, if exceeded, may result in significant risk to aquatic organisms. CCs were determined by dividing acute or chronic toxicity values by an assessment factor (ranging from one to 1,000) that incorporates the uncertainty associated with toxicity data. Chemicals were also ranked according to established EPA criteria for aquatic toxicity of high, moderate, or low concern.

Section 3.3 of the CTSA presents ecological hazard data, CCs, and aquatic toxicity concern levels for each of the non-proprietary MHC chemicals. Table ES.2 presents the number of MHC chemicals evaluated for each technology, the number of chemicals in each technology with aquatic toxicity of high, moderate, or low concern, and the chemicals with the lowest CC by technology.

Limitations

There are a number of limitations to the project, both because of the limit of the project's resources, the predefined scope of the project, and uncertainties inherent to risk characterization techniques. Some of the limitations related to the risk, competitiveness, and conservation components of the CTSA are summarized below. More detailed information on limitations and uncertainties for a particular portion of the assessment is given in the applicable sections of this document. A limitation common to all components of the assessment is that the MHC chemical products assessed in this report were voluntarily submitted by participating suppliers and may not represent the entire MHC technology market.

Table ES.2 Aquatic Hazard Data

MHC Technology	No. of Chemicals Evaluated[a]	No. of Chemicals by Aquatic Hazard Concern Level[a]			Chemical with Lowest CC
		High	Moderate	Low	
Electroless Copper	50[b]	9	19	21	copper sulfate (0.00002 mg/l)
Carbon	8[b]	2	2	3	copper sulfate (0.00002 mg/l)
Conductive Ink	11[b]	2	1	7	silver (0.000036 mg/l)
Conductive Polymer	6	0	1	5	peroxymonosulfuric acid (0.030 mg/l)
Graphite	13	3	3	7	copper sulfate (0.00002 mg/l)
Non-Formaldehyde Electroless Copper	10	3	3	4	copper sulfate (0.00002 mg/l)
Organic-Palladium	7	2	3	2	sodium hypophosphite (0.006 mg/l)
Tin-Palladium	26[b]	9	6	10	copper sulfate (0.00002 mg/l)

[a] This includes chemicals from both publicly-available and proprietary data. This indicates the number of unique chemicals; there is some overlap between public and proprietary lists for electroless copper. For technologies with more than one chemical supplier (i.e., electroless copper, graphite, and tin-palladium), all chemicals may not be present in any one product line.
[b] No aquatic hazard data available for one chemical.

Risk

The risk characterization is a screening level assessment of multiple chemicals used in MHC technologies. The focus of the risk characterization is on chronic (long-term) exposure to chemicals that may cause cancer or other toxic effects, rather than on acute toxicity from brief exposures to chemicals. The exposure assessment and risk characterization use a "model facility" approach, with the goal of comparing the exposures and health risks of the MHC process alternatives to the baseline non-conveyorized electroless copper technology. Characteristics of the model facility were aggregated from questionnaire data, site visits, and other sources. This approach does not result in an absolute estimate or measurement of risk.

In addition, the exposure and risk estimates reflect only a portion of the potential exposures within a PWB manufacturing facility. Many of the chemicals found in MHC technologies may also be present in other process steps of PWB manufacturing, and other risk concerns for human health and the environment may occur from these other process steps. Incremental reduction of exposures to chemicals of concern from an MHC process, however, will reduce cumulative exposures from all sources in a PWB facility, provided that increased production does not increase plant-wide pollution.

Finally, as discussed previously, Enthone-OMI, MacDermid, and Shipley submitted publicly-available chemistry information for evaluation in the risk characterization, but declined to submit proprietary information. Atotech submitted publicly-available information and limited proprietary information for one chemical in one product line. Electrochemicals, LeaRonal, and Solution Technology Systems submitted both publicly-available and proprietary chemistry information. The absence of complete information on proprietary chemical ingredients in products supplied by Atotech, Enthone-OMI, MacDermid, and Shipley is a significant source of uncertainty in the risk characterization.

Competitiveness

The Performance Demonstration was designed to provide a snapshot of the performance of different MHC technologies. The test methods used to evaluate performance were intended to indicate characteristics of a technology's performance, not to define parameters of performance or to substitute for thorough on-site testing. Because the test sites were not chosen randomly, the sample may not be representative of all PWB manufacturing facilities in the U.S. (although there is no specific reason to believe they are not representative).

The cost analysis presents comparative costs of using an MHC technology in a model facility to produce 350,000 ssf of PWB. As with the risk characterization, this approach results in a comparative evaluation of cost, not an absolute evaluation or determination. The cost analysis focuses on private costs that would be incurred by facilities implementing a technology. It does not evaluate community benefits or costs, such as the effects on jobs from implementing a more efficient MHC technology. However, the Social Benefits/Costs Assessment (see Section 7.2) qualitatively evaluates some of these external (i.e., external to the decision-maker at a PWB facility) benefits and costs.

The regulatory information contained in the CTSA may be useful in evaluating the benefits of moving away from processes containing chemicals that trigger compliance issues. However, this document is not intended to provide compliance assistance. If the reader has questions regarding compliance concerns, they should contact their federal, state, or local authorities.

Conservation

The analysis of energy and water consumption is also a comparative analysis, rather than an absolute evaluation or measurement. Similar to the cost analysis, consumption rates were estimated based on using an MHC technology in a model facility to produce 350,000 ssf of PWB.

IV. CLEANER TECHNOLOGIES SUBSTITUTES ASSESSMENT RESULTS

Occupational Exposures and Health Risks

Health risks to workers were estimated for inhalation exposure to vapors and aerosols from MHC baths and for dermal exposure to MHC bath chemicals. Inhalation exposure estimates are based on the assumptions that emissions to indoor air from conveyorized lines are negligible, that the air in the process room is completely mixed and chemical concentrations are constant over time, and that no vapor control devices (e.g., bath covers) are used in non-conveyorized lines. Dermal exposure estimates are based on the assumption that workers do not wear gloves[2] and that all non-conveyorized lines are operated by manual hoist. Dermal exposure to line operators on non-conveyorized lines could occur from routine line operation and maintenance (e.g., bath replacement, filter replacement). Dermal exposure to line operators on conveyorized lines was assumed to occur from bath maintenance activities alone.

The exposure assessment for this risk characterization used, whenever possible, a combination of central tendency and high-end assumptions (i.e., 90 percent of actual values are expected to be less) to yield an overall high-end exposure estimate. Some values used in the exposure calculations, however, are better characterized as "what-if,"[3] especially pertaining to bath concentrations, use of gloves, and process area ventilation rates for a model facility. Because some part of the exposure assessment for both inhalation and dermal exposures qualifies as a "what-if" descriptor, the entire assessment should be considered "what-if."

Risk results indicate that alternatives to the non-conveyorized electroless copper process pose lower occupational risks due to reduced cancer risks and to the reduced number of inhalation and dermal risk concerns for the alternatives. However, there are occupational inhalation risk concerns for some chemicals in the non-formaldehyde electroless copper and tin-palladium non-conveyorized processes. In addition, there are occupational risk concerns for dermal contact with some chemicals in the conveyorized electroless copper process, the non-conveyorized non-formaldehyde electroless copper process, and in the organic-palladium and tin-palladium processes for either conveyorized or non-conveyorized equipment. Finally, occupational health risks could not be quantified for one or more of the chemicals used in each of the MHC technologies. This is due to the fact that proprietary chemicals in the baths were not identified by suppliers of some chemical products and to missing toxicity or chemical property data for some chemicals known to be present in the baths.

Table ES.3 presents chemicals of concern for potential occupational risk from inhalation. Table ES.4 presents chemicals of concern for potential occupational risk from dermal contact.

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[2] Many PWB manufacturers report that their employees routinely wear gloves in the process area. However, risk from dermal contact was estimated assuming workers do not wear gloves to account for those workers who do not wear proper personal protective equipment.

[3] A "what-if" description represents an exposure estimate based on postulated questions, making assumptions based on limited data where the distribution is unknown.

Table ES.3 MHC Chemicals of Concern for Potential Occupational Inhalation Risk

Chemical[a]	Non-Conveyorized Process[b]		
	Electroless Copper	Non-Formaldehyde Electroless Copper	Tin-Palladium
Alkene Diol	✔		
Copper Chloride	✔		
Ethanolamine	✔		✔
2-Ethoxyethanol	✔		
Ethylene Glycol	✔		
Formaldehyde	✔		
Formic Acid	✔		
Methanol	✔		
Sodium Hydroxide	✔		
Sulfuric Acid[c]	✔	✔	✔

[a] For technologies with more than one chemical supplier (e.g., electroless copper and tin-palladium), chemicals of concern that are present in all of the product lines evaluated are indicated in bold.
[b] Occupational inhalation exposure from conveyorized lines was assumed to be negligible.
[c] Sulfuric acid was listed on the MSDSs for all of the electroless copper lines evaluated and four of the five tin-palladium lines evaluated.

Table ES.4 MHC Chemicals of Concern for Potential Occupational Dermal Risk

Chemical[a]	Electroless Copper			Non-Formaldehyde Electroless Copper	Tin-Palladium			Organic-Palladium		
	Line Operator		Lab Tech (NC or C)	Line Operator (NC)	Line Operator		Lab Tech (NC or C)	Line Operator		Lab Tech (NC or C)
	NC	C			NC	C		NC	C	
Copper Chloride	✔	✔	✔		✔	✔	✔			
Fluoroboric Acid	✔	✔	✔		✔	✔	✔			
Formaldehyde	✔	✔								
Nitrogen Heterocycle	✔	✔								
Palladium[b]	✔	✔	✔		✔	✔	✔			
Palladium Chloride[b]					✔	✔	✔			
Palladium Salt								✔	✔	✔
Sodium Carboxylate	✔	✔								
Sodium Chlorite	✔	✔		✔						
Stannous Chloride[c]	✔			✔	✔	✔				
Tin Salt		✔								

[a] For technologies with more than one chemical supplier (e.g., electroless copper and tin-palladium), chemicals of concern that are present in all of the product lines evaluated are indicated in bold.
[b] Palladium or palladium chloride was listed on the MSDSs for three of the five tin-palladium lines evaluated. The MSDSs for the two other lines did not list a source of palladium. Palladium and palladium chloride are not listed on the MSDSs for all of the electroless copper lines evaluated.
[c] Stannous chloride was listed on the MSDSs for four of the five tin-palladium lines evaluated. The MSDSs for the remaining line did not list a source of tin. Stannous chloride is not listed on the MSDSs for all of the electroless copper lines evaluated.
NC: Non-Conveyorized.
C: Conveyorized.

Occupational cancer risks were estimated for inhalation exposure to formaldehyde and alkyl oxide in the non-conveyorized electroless copper process, and for dermal exposure to cyclic ether and alkyl oxide in the conveyorized graphite, conveyorized electroless copper, and non-conveyorized electroless copper processes. Formaldehyde has been classified by EPA as Group B1, a Probable Human Carcinogen. Results indicate clear concern for formaldehyde inhalation exposure; the upper bound excess individual cancer risk estimate for line operators in the non-conveyorized electroless copper process from formaldehyde inhalation may be as high as one in 1,000, but may be 50 times less, or one in 50,000.[4] Inhalation risks to other workers were assumed to be proportional to the amount of time spent in the process area, which ranged from three percent to 61 percent of the risk for a line operator. Occupational risks associated with dermal and inhalation exposure to cyclic ether and alkyl oxide were below 1×10^{-6} (one in one million) for the graphite and electroless copper processes and are therefore considered to be of low concern.

Other non-proprietary chemicals in the MHC processes are suspected carcinogens. Dimethylformamide and carbon black have been determined by the International Agency for Research on Cancer (IARC) to possibly be carcinogenic to humans (IARC Group 2B). Like formaldehyde, the evidence for carcinogenic effects is based on animal data. However, unlike formaldehyde, slope factors are not available for either chemical. There are potential cancer risks to workers from both chemicals, but they cannot be quantified. Dimethylformamide is used in the electroless copper process. Workplace exposures have been estimated but cancer potency and cancer risk are unknown. Carbon black is used in the carbon and conductive ink processes. Occupational exposure due to air emissions from the carbon baths in the carbon process is expected to be negligible because this process is typically conveyorized and enclosed. There may be some airborne carbon black, however, from the drying oven steps. Exposures from conductive ink were not characterized. One proprietary chemical used in the electroless copper process, trisodium acetate amine B, was determined to possibly be carcinogenic to humans but does not have an established slope factor.

Public Exposures and Health Risks

Public health risks were estimated for inhalation exposure only for the general population living near a facility. Environmental releases and risk from exposure to contaminated surface water were not quantified due to a lack of data; chemical constituents and concentrations in wastewater resulting only from the MHC process could not be adequately characterized. Public health risk estimates are based on the assumption that emissions from both conveyorized and non-conveyorized process configurations are steady-state and vented to the outside. Risk was not characterized for short-term exposures to high levels of hazardous chemicals when there is a spill, fire, or other release.

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[4] To provide further information on the possible variation of formaldehyde exposure and risk, an additional exposure estimate was provided in the Risk Characterization (Section 3.4) using average and median values (rather than high-end) as would be done for a central tendency exposure estimate. This results in approximately a 35-fold reduction in occupational formaldehyde exposure and risk from the estimates presented here.

The risk indicators for ambient exposures to humans, although limited to airborne releases, indicate low concern from all MHC technologies for nearby residents. The upper bound excess individual cancer risk from formaldehyde inhalation for nearby residents from the non-conveyorized electroless copper process was estimated to be from approaching zero to 1×10^{-7} (one in ten million), and from approaching zero to 3×10^{-7} (one in three million) for the conveyorized electroless copper process. Formaldehyde has been classified by EPA as Group B1, a Probable Human Carcinogen. The risk characterization for ambient exposure to MHC chemicals also indicates low concern from the estimated air concentrations for chronic non-cancer effects. The upper bound excess individual cancer risk for nearby residents from alkyl oxide in the conveyorized graphite process was estimated to be from approaching zero to 9×10^{-11} (one in 11 billion); in the non-conveyorized electroless copper process from approaching zero to 1×10^{-11} (one in 100 billion); and in the conveyorized electroless copper process from approaching zero to 3×10^{-11} (one in 33 billion). All hazard quotients are less than one for ambient exposure to the general population, and all MOEs for ambient exposure are greater than 1,000 for all processes, indicating low concern from the estimated air concentrations for chronic non-cancer effects.

Ecological Hazards

The CTSA methodology typically evaluates ecological risks in terms of risks to aquatic organisms in streams that receive treated or untreated effluent from manufacturing processes. Stream concentrations of MHC chemicals were not available, however, and could not be estimated because of insufficient chemical characterization of constituents and their concentrations in facility wastewater. This is primarily because PWB manufacturers combine effluent from the MHC process line with effluent from other manufacturing steps prior to on-site wastewater treatment or discharge. No information was available on the contribution of the MHC process effluents to overall pollutant discharges. To qualitatively assess risk to aquatic organisms, MHC chemicals were ranked based on aquatic toxicity values according to established EPA criteria for aquatic toxicity of high, moderate, or low concern. Aquatic hazards data are summarized in Section III of the Executive Summary and Section 3.3 of the CTSA.

Process Safety

In order to evaluate the chemical safety hazards of the various MHC technologies, MSDSs for chemical products used with each of the MHC technologies were reviewed. Table ES.5 summarizes the hazardous properties listed on MSDSs for MHC chemical products.

Other potential chemical hazards can occur because of hazardous decomposition of chemical products, or chemical product incompatibilities with other chemicals or materials. With few exceptions, most chemical products used in MHC technologies can decompose under specific conditions to form potentially hazardous chemicals. In addition, all of the MHC processes have chemical products with incompatibilities that can pose a threat to worker safety if the proper care is not taken to prevent such occurrences.

Table ES.5 Hazardous Properties of MHC Chemical Products

MHC Technology	Types of Hazardous Properties Reported on MSDSs[a]
Electroless Copper	flammable, combustible, explosive, fire hazard, corrosive, oxidizer, reactive, unstable, acute health hazard, chronic health hazard, eye damage
Carbon	flammable, corrosive, oxidizer, reactive, acute health hazard, chronic health hazard, eye damage
Conductive Ink	explosive, eye damage
Conductive Polymer[b]	flammable, corrosive, eye damage
Graphite	fire hazard, corrosive, oxidizer, unstable, acute health hazard, chronic health hazard, eye damage
Non-Formaldehyde Electroless Copper	flammable, corrosive, oxidizer, reactive, acute health hazard, chronic health hazard, eye damage
Organic-Palladium[b]	unstable, eye damage
Tin-Palladium	flammable, combustible, explosive, fire hazard, corrosive, reactive, sensitizer, acute health hazard, chronic health hazard, eye damage

[a] For technologies with more than one chemical supplier (i.e., electroless copper, graphite, and tin-palladium), all hazardous properties may not be listed for any one product line.
[b] Based on German equivalent of MSDS, which may not have as stringent reporting requirements as U.S. MSDS.

Work-related injuries from equipment, improper use of equipment, bypassing equipment safety features, failure to use personal protective equipment, and physical stresses that may appear gradually as a result of repetitive motion are all potential process safety hazards to workers. Reducing the potential for work-related injuries is critical in an effective and ongoing safety training program. Without appropriate training, the number of work-related accidents and injuries is likely to increase, regardless of the technology used.

Performance

The performance of the MHC technologies was tested using production run tests. In order to complete this evaluation, PWB panels, designed to meet industry “middle-of-the-road” technology, were manufactured at one facility, run through individual MHC lines at 26 facilities, then electroplated at one facility. The panels were electrically prescreened, followed by electrical stress testing and mechanical testing, in order to distinguish variability in the performance of the MHC interconnect. The Performance Demonstration was conducted with extensive input and participation from PWB manufacturers, their suppliers, and PWB testing laboratories. The test vehicle was a 24" x 18" x 0.062" 8-layer panel. (See Section 4.1 for a detailed description of the test vehicle.) Each test site received three panels for processing through the MHC line.

Test sites were submitted by suppliers of the technologies, and included production facilities, testing facilities (beta sites), and supplier testing facilities. Because the test sites were not chosen randomly, the sample may not be representative of all PWB manufacturing facilities (although there is no specific reason to believe that they are not representative). In addition, the number of test sites for each technology ranged from one to ten. Due to the smaller number of test sites for some technologies, results for these technologies could more easily be due to chance than the results from technologies with more test sites. Statistical relevance could not be determined.

Product performance for this study was divided into two functions: plated through-hole (PTH) cycles to failure and the integrity of the bond between the internal lands (post) and PTH (referred to as "post separation"). The PTH cycles to failure observed in this study is a function of both electrolytic plating and MHC process. The results indicate that each MHC technology has the capability to achieve comparable (or superior) levels of performance to electroless copper. Post separation results indicated percentages of post separation that were unexpected by many members of the industry. It was apparent that all MHC technologies, including electroless copper, are susceptible to this type of failure.

Cost

Comparative costs were estimated using a hybrid cost model which combined traditional costs with simulation modeling and activity-based costs. The cost model was designed to determine the total cost of processing a specific amount of PWBs through a fully operational MHC line, in this case, 350,000 ssf. The cost model did not estimate start-up costs for a facility switching to an alternative MHC technology or the costs of other process changes that may be required to implement an alternative technology. Total costs were divided by the throughput (350,000 ssf) to determine a unit cost in dollars per ssf.

The cost components considered include capital costs (primary equipment, installation, and facility costs), materials costs (limited to chemical costs), utility costs (water, electricity, and natural gas costs), wastewater costs (limited to wastewater discharge cost), production costs (production labor and chemical transport costs), and maintenance costs (tank clean up, bath setup, sampling and analysis, and filter replacement costs). Other cost components may contribute significantly to overall costs, but could not be quantified. These include wastewater treatment cost, sludge recycling and disposal cost, other solid waste disposal costs, and quality costs.

Table ES.6 presents results of the cost analysis, which indicate all of the alternatives are more economical than the non-conveyorized electroless copper process. In general, conveyorized processes cost less than non-conveyorized processes. Chemical cost was the single largest component cost for nine of the ten processes. Equipment cost was the largest cost for the non-conveyorized electroless copper process. Three separate sensitivity analyses of the results indicated that chemical costs, production labor costs, and equipment costs have the greatest effect on the overall cost results.

Table ES.6 Cost Analysis Results[a]

MHC Technology	Average Cost		Capital Cost		Chemical Cost		Water Cost		Electricity Cost	
	$/ssf	% change	$/ssf	% change	$/ssf	% change	$/ssf	% change	$/ssf	% change
Electroless Copper, non-conveyorized (BASELINE)	$ 0.51		$ 0.24		$ 0.06		$ 0.02		$ 0.008	
Electroless Copper, conveyorized	$ 0.15	-71	$ 0.03	-88	$ 0.06	0	$ 0.002	-90	$ 0.002	-75
Carbon, conveyorized	$ 0.18	-65	$ 0.03	-88	$ 0.10	+66	$ 0.002	-90	$ 0.001	-88
Conductive Polymer, conveyorized	$ 0.09	-82	$ 0.02	-92	$ 0.03	-50	$ 0.001	-95	$ 0.001	-88
Graphite, conveyorized	$ 0.22	-57	$ 0.01	-96	$ 0.17	+183	$ 0.001	-95	$ 0.004	-50
Non-Formaldehyde Electroless Copper, non-conveyorized	$ 0.40	-22	$ 0.11	-54	$ 0.20	+233	$ 0.01	-50	$ 0.004	-50
Organic-Palladium, non-conveyorized	$ 0.15	-71	$ 0.02	-92	$ 0.08	+33	$ 0.002	-90	$ 0.001	-88
Organic-Palladium, conveyorized	$ 0.17	-67	$ 0.02	-92	$ 0.08	+33	$ 0.002	-90	$ 0.002	-75
Tin-Palladium, non-conveyorized	$ 0.14	-73	$ 0.02	-92	$ 0.06	0	$ 0.003	-85	$ 0.002	-75
Tin-Palladium, conveyorized	$ 0.12	-77	$ 0.01	-96	$ 0.07	+17	$ 0.001	-95	$ 0.001	-88

MHC Technology	Natural Gas Cost		Wastewater Cost		Production Cost		Maintenance Cost	
	$/ssf	% change	$/ssf	% change	$/ssf	% change	$/ssf	% change
Electroless Copper, non-conveyorized (BASELINE)	$ -		$ 0.04		$ 0.11		$ 0.04	
Electroless Copper, conveyorized	$ -	NA	$ 0.004	-90	$ 0.02	-82	$ 0.03	-25
Carbon, conveyorized	$ 0.001	NA	$ 0.005	-88	$ 0.03	-73	$ 0.01	-75
Conductive Polymer, conveyorized	$ -	NA	$ 0.003	-93	$ 0.02	-82	$ 0.02	-50
Graphite, conveyorized	$ 0.0004	NA	$ 0.002	-95	$ 0.02	-82	$ 0.01	-75
Non-Formaldehyde Electroless Copper, non-conveyorized	$ -	NA	$ 0.01	-75	$ 0.05	-55	$ 0.02	-50
Organic-Palladium, non-conveyorized	$ -	NA	$ 0.005	-88	$ 0.02	-82	$ 0.03	-25
Organic-Palladium, conveyorized	$ -	NA	$ 0.004	-90	$ 0.02	-82	$ 0.03	-25
Tin-Palladium, non-conveyorized	$ -	NA	$ 0.007	-83	$ 0.03	-73	$ 0.02	-50
Tin-Palladium, conveyorized	$ -	NA	$ 0.002	-95	$ 0.02	-82	$ 0.02	-50

[a] Table lists costs and percent change in cost from baseline.
NA: Not Applicable. Percent change cannot be calculated because baseline has zero cost in this cost category.

Regulatory Status

Discharges of MHC chemicals may be restricted by federal, state or local air, water or solid waste regulations, and releases may be reportable under the federal Toxic Release Inventory program. Federal environmental regulations were reviewed to determine the federal regulatory status of MHC chemicals.[5] Table ES.7 lists the number of chemicals used in an MHC technology that are subject to federal environmental regulations. Different chemical suppliers of a technology do not always use the same chemicals in their particular product lines. Thus, all of these chemicals may not be present in any one product line.

International Information

Several suppliers indicated that market shares of the MHC alternatives are increasing internationally quicker than they are increasing in the U.S. The cost-effectiveness of an alternative has been the main driver causing PWB manufacturers abroad to switch from an electroless copper process to one of the newer alternatives. In addition to the increased capacity and decreased labor requirements of some of the MHC alternatives over the electroless copper process, environmental concerns also affected the process choice. For instance, the rate at which an alternative consumes water and the presence or absence of strictly regulated chemicals are two factors which have a substantial effect on the cost-effectiveness of MHC alternatives abroad.

Resource Conservation Summary

Resources typically consumed by the operation of an MHC process include water used for rinsing panels, process chemicals used on the process line, energy used to heat process baths and power equipment, and wastewater treatment chemicals. The energy and water consumption rates of the MHC process alternatives were calculated to determine if implementing an alternative to the baseline process would reduce consumption of these resources during the manufacturing process. Process chemical and treatment chemical consumption rates could not be quantified due to the variability of factors that affect the consumption of these resources. Table ES.8 presents the energy and water consumption rates of MHC technologies.

The rate of water consumption is directly related to the rate of wastewater generation. Most PWB facilities discharge process rinse water to an on-site wastewater treatment facility for pretreatment prior to discharge to a publicly-owned treatment works (POTW). A pollution prevention analysis identified a number of pollution prevention techniques that can be used to reduce rinse water consumption. These include use of more efficient rinse configurations, use of flow control technologies, and use of electronic sensors to monitor contaminant concentrations in rinse water. Further discussion of these and other pollution prevention techniques can be found in the Pollution Prevention section of the CTSA (Section 6.1) and in PWB Project pollution prevention case studies, which are available from the Pollution Prevention Information Clearinghouse (see p. ii).

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[5] In some cases, state or local requirements may be more restrictive than federal requirements. However, due to resource limitations, only federal regulations were reviewed.

Table ES.7 Regulatory Status of MHC Technologies[a]

MHC Technology	Chemicals Subject to Applicable Regulation																
	CWA				SDWA		CAA			SARA 110	EPCRA		TSCA			RCRA Waste	
	304b	307a	311	Priority Pollutant	NPDWR	NSDWR	111	112b	112r		302a	313	8d HSDR	MTL	8a PAIR	P	U
Electroless Copper	4	4	13	8	4	5	8	8	2	6	6	13	2	4	3	2	4
Carbon	1	1	3	2	1	1				1		1					
Conductive Ink	2	2		2		1	5	3		1		2	2		3		1
Conductive Polymer			3				1				1	2					
Graphite	2	1	3	1	1	1	1		1	2	2	3					
Non-Formaldehyde Electroless Copper	1	1	5	1	1	1	1	1	1	3	3	4		1	1		
Organic-Palladium			2					1	1		1	1					
Tin-Palladium	2	2	7	2	3	3	3	1	1	6	3	6		3	3		1

[a] Tables 4.38 through 4.45 in Section 4.3 give more detailed regulatory summaries by MHC technology, including potentially regulated chemical names. PWB manufacturers can refer to the MSDSs for the MHC chemical products they use to determine if a particular chemical is present.

Abbreviations and definitions:

CAA - Clean Air Act
CAA 111 - Standards of Performance for New Stationary Sources of Air Pollutants - Equipment Leaks Chemical List
CAA 112b - Hazardous Air Pollutant
CAA 112r - Risk Management Program
CWA - Clean Water Act
CWA 304b - Effluent Limitations Guidelines
CWA 307a - Toxic Pollutants
CWA 311 - Hazardous Substances
CWA Priority Pollutants
EPCRA - Emergency Planning and Community Right-to-Know Act
EPCRA 302a - Extremely Hazardous Substances
EPCRA 313 - Toxic Chemical Release Inventory
RCRA - Resource Conservation and Recovery Act
RCRA P Waste - Listed acutely hazardous waste
RCRA U Waste - Listed hazardous waste
SARA - Superfund Amendments and Reauthorization Act
SARA 110 - Superfund Site Priority Contaminant
SDWA - Safe Drinking Water Act
SDWA NPDWR - National Primary Drinking Water Rules
SDWA NSDWR - National Secondary Drinking Water Rules
TSCA - Toxic Substances Control Act
TSCA 8d HSDR - Health & safety data reporting rules
TSCA MTL - Master Testing List
TSCA 8a PAIR - Preliminary Assessment Information Rule

Table ES.8 Energy and Water Consumption Rates of MHC Technologies

Process Type	Water Consumption (gal/ssf)	Energy Consumption (Btu/ssf)
Electroless Copper, non-conveyorized (BASELINE)	11.7	573
Electroless Copper, conveyorized	1.15	138
Carbon, conveyorized	1.29	514
Conductive Polymer, conveyorized	0.73	94.7
Graphite, conveyorized	0.45	213
Non-Formaldehyde Electroless Copper, non-conveyorized	3.74	270
Organic-Palladium, non-conveyorized	1.35	66.9
Organic-Palladium, conveyorized	1.13	148
Tin-Palladium, non-conveyorized	1.80	131
Tin-Palladium, conveyorized	0.57	96.4

Social Benefits/Costs Assessment

The social benefits and costs of the MHC technologies were qualitatively assessed to compare the benefits and costs of switching from the baseline technology to an alternative, while considering both the private and external costs and benefits. Private costs typically include any direct costs incurred by the decision-maker and are generally reflected in the manufacturer's balance sheet. In contrast, external costs are incurred by parties other than the primary participants to the transaction. Economists distinguish between private and external costs because each will affect the decision-maker differently. Although external costs are real costs to some members of society, they are not incurred by the decision-maker and firms do not normally take them into account when making decisions.

Table ES.9 compares some of the relative benefits and costs of each technology to the baseline, including production costs, worker health risks, public health risks, aquatic toxicity concerns, water consumption, and energy consumption. The effects on jobs of wide-scale adoption of an alternative is not included in the table because the potential for job losses was not evaluated in the CTSA. However, the results of the CTSA cost analysis suggest there are significantly reduced labor requirements for the alternatives. Clearly, if manufacturing jobs were lost, it would be a significant external cost to the community and should be considered by PWB manufacturers when choosing among MHC technologies.

While each alternative presents a mixture of private and external benefits and costs, it appears that each of the alternatives have social benefits as compared to the baseline. In addition, at least three of the alternatives appear to have social benefits over the baseline in every category. These are the conveyorized conductive polymer process and both conveyorized and non-conveyorized organic-palladium processes. Note, however, that the supplier of these technologies declined to provide complete information on proprietary chemical ingredients, meaning health risks could not be fully assessed.

Table ES.9 Relative Benefits and Costs of MHC Alternatives Versus Baseline

MHC Technology	Production Costs ($/ssf)	Number of Chemicals of Concern[a]				Water Consumption (gal/ssf)	Energy Consumption (Btu/ssf)
		Worker Health Risks[b,c,d]		Public Health Risks[e]	High Aquatic Toxicity Concern[b,f]		
		Inhalation	Dermal	Inhalation			
Electroless Copper, non-conveyorized (BASELINE)	$0.51	10	8	0[g]	9	11.7	573
Electroless Copper, conveyorized	↗↗	↗↗	↔	↔[h]	↔	↗↗	↗↗
Carbon, conveyorized	↗↗	↗↗	↗↗	↗	↔	↗↗	↔
Conductive Polymer, conveyorized	↗↗	↗↗	↗↗	↗	↗	↗↗	↗↗
Graphite, conveyorized	↗↗	↗↗	↗↗[i]	↗[j]	↔	↗↗	↗↗
Non-Formaldehyde Electroless Copper, non-conveyorized	↗	↗	↗	↗	↔	↗↗	↗↗
Organic-Palladium, non-conveyorized	↗↗	↗↗	↗	↗	↗	↗↗	↗↗
Organic-Palladium, conveyorized	↗↗	↗↗	↗	↗	↗	↗↗	↗↗
Tin-Palladium, non-conveyorized	↗↗	↗	↗	↗	↔	↗↗	↗↗
Tin-Palladium, conveyorized	↗↗	↗↗	↗	↗	↔	↗↗	↗↗

[a] Includes proprietary chemicals that were identified.

[b] For technologies with more than one chemical supplier (i.e., electroless copper, graphite, and tin-palladium) all chemicals may not be present in any one product line.

[c] For the most exposed individual (i.e., an MHC line operator).

[d] Because the risk characterization did not estimate the number of incidences of adverse health outcomes, the amount of reduced risk benefit cannot be quantifed. However, based on the level of formaldehyde risk and the number of chemicals of concern for the baseline, it appears all of the alternatives have at least some reduced risk benefits from the baseline.

[e] Because the risk characterization did not estimate the number of incidences of adverse health outcomes, the amount of reduced risk benefit cannot be quantifed. However, based on the level of formaldehyde risk for the baseline, it appears all of the alternatives except the conveyorized electroless copper process have at least some reduced risk benefits from the baseline.

[f] Technologies using copper sulfate were assigned a neutral benefit or cost; other technologies were assigned "some benefit" because none of their chemicals are as toxic to aquatic organisms as copper sulfate. This assessment is based on hazard, not risk.

[g] No chemical risks above concern levels. However, it should be noted that formaldehyde cancer risks as high as 1×10^{-7} were estimated.

[h] No chemical risks above concern levels. However, it should be noted that formaldehyde cancer risks as high as 3×10^{-7} were estimated.

[i] No chemical risks above concern levels. However, it should be noted that proprietary chemical cancer risks as high as 1×10^{-7} were estimated.

[j] No chemical risks above concern levels. However, it should be noted that proprietary chemical cancer risks as high as 9×10^{-11} were estimated.

Key:

↔ - Neutral, less than 20 percent increase or decrease from baseline.

↗ - Some benefit, 20 to <50 percent decrease from baseline.

↗↗ - Greater benefit, 50 percent or greater decrease from baseline.

V. CONCLUSIONS

The CTSA evaluated the risk, competitiveness, and resource requirements of seven technologies for performing the MHC function during PWB manufacturing. These technologies are electroless copper, carbon, conductive polymer, graphite, non-formaldehyde electroless copper, organic-palladium, and tin palladium. Chemical and process information are also presented for a conductive ink technology.

The results of the CTSA suggest that the alternatives to traditional non-conveyorized electroless copper processes (the baseline process) not only have environmental and economic benefits, but also perform the MHC function as well as the baseline. While there appears to be enough information to show that a switch away from traditional electroless copper processes has reduced risk benefits, there is not enough information to compare the alternatives to this process among themselves for all their environmental and health consequences. This is because not all proprietary chemicals have been identified, and because toxicity values are not available for some chemicals. In addition, it is important to note that there are additional factors beyond those assessed in this CTSA which individual businesses may consider when choosing among alternatives. The actual decision of whether or not to implement an alternative is made outside of the CTSA process.

To assist PWB manufacturers who are considering switching to an MHC alternative, the DfE PWB Project has prepared an implementation guide that describes lessons learned by other PWB manufacturers who have switched from non-conveyorized electroless copper to one of the alternative processes.[6] In addition, the University of Tennessee Department of Industrial Engineering can provide technical support to facilities that would like to use the cost model developed for the CTSA to estimate their own manufacturing costs should they switch to an MHC alternative.

[6] *Implementing Cleaner Technologies in the Printed Wiring Board Industry: Making Holes Conductive* (EPA 744-R-97-001, February 1997). This and other DfE PWB Project documents can be obtained by contacting EPA's Pollution Prevention Information Clearinghouse at (202) 260-1023.